Social Spatial Heterogeneity and System Entrainment in Modeling Human and Nature Dynamics

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Abstract. In the context of sustainable development, a complex adaptive systems framework can help address the coupling of macro social, environmental and economic constraints and opportunities with individual agency. Using a simple evolutionary game approach, we fuse endogenously derived socio-economic system dynamics from human and nature dynamics (HANDY) theory with Prisoner's Dilemma, spatial intra-societal economic transactions. We explore the potential of spectral information from the social network adjacency matrices to predict synchronization dynamics and see how behavioral social spatial heterogeneity entrain with wealth, carrying capacity and population.

Keywords: Sustainable development · Complex adaptive systems · Network Analysis· Agent-based modeling · System dynamics · Game theory

1 Introduction

Social scientists have long identified dynamic linkages between economic development, population dynamics, and environment [8][6][11]. Starting in ecological economics, the human and nature dynamics (HANDY) perspective is a quantitative, trans-disciplinary approach to understanding modernization and development through interdependent economic and social forces at the aggregate society level. Here we extend previous work by Motesharrei.'s [11] novel systems dynamic representation of societal level theory towards integrated macro-micro scales in a complex adaptive systems framework using an agent-based approach. As macroscopic structures emerging from microscopic events lead to entrainment and modification of both, co-evolutionary processes are created over time [13]. Similar to Abdollahian et al [1-3] and Yang [15], we posit a new, approach where agency matters: individual game interactions, strategy decisions and historical outcomes determine an individual's experience. These decisions are constrained or incentivized by the changing macro economic, cultural, social and political environment via human and nature dynamics theory, conditioned on individual attributes at any particular time. Emergent behavior results from individuals' current feasible choice set, conditioned upon past behavior, event history and macro societal outcomes. Conversely, progress on economic development, the formation of cultural mores, societal norms and democratic preferences emerge from individuals' behavior interactions.

To explore potential real-world applications of this analysis, we consider the potential explanatory power of information contained in the eigenspectrum of the Laplacian matrix describing the dynamic adjacency matrices of the underlying social network of relationships between competing agents. This approach, borrowed from the theoretical physics literature, allows potential mean-field style analysis of an otherwise intractably complex game.

2 HANDY Background

HANDY postulates a development process in which inequality and use of resources play a critical role. Brander and Taylor [5] developed an ancestor model of population and renewable resource dynamics and demonstrated that reasonable parameter values can produce cyclical feast and famine patterns of population and resources. Their model shows that a system with a slow-growing resource base will exhibit overshooting and collapse, whereas a more rapidly growing resource base will produce an adjustment of population and resources toward equilibrium values. However, this approach does not include a central component of population dynamics: economic stratification and the accumulation of wealth.

Inspired by a Lotka-Voltera model at the core, Motesharrei et al. [11] develop a human population dynamics model by adding accumulated wealth and economic inequality. They develop and measure "carrying capacity" and show it to be a potentially practical means for early detection of societal collapse. When a population surpasses the carrying capacity, starvation or migration can threaten to significantly impact population levels and rates of change. However, humans can also accumulate wealth and then draw down resources when production cannot match consumption needs. Empirically, they posit that accumulated surpluses are not evenly distributed throughout society. As elites control resources normally, they could leave the mass of the population, while producing a portion of generated wealth, with only a small portion of it usually at or just above subsistence levels [7][4]. While the Brander–Taylor model has only two equations, Motesharrei et al's model supplements an additional two equations to predict the evolution of nature, accumulated wealth, elites and commoners as an interdependent, asymmetric first order system. Their HANDY equations are given by:

$$\begin{cases} \dot{x}_C = \beta_C x_C - \alpha_C x_C \\ \dot{x}_E = \beta_E x_E - \alpha_E x_E \\ \dot{y} = \gamma y(\lambda - y) - \delta x_C y \\ \dot{w} = \delta x_C y - C_C - C_E. \end{cases}$$

In this system, the total population is divided between the two variables, χ_C and χ_E, representing commoners and elites respectively. The population grows at a birth rate β and decreases at a death rate α. In their model, β is assumed to be constant for both elites and commoners but α depends on wealth. The equation for nature includes a regeneration or gain term $\gamma Y(\lambda - Y)$, and a depletion or loss term $-\delta \chi_C Y$. Technological change can make the use of resources more efficient, but it also tends to raise both per capita resource consumption as well as resource extraction scales. Thus accumulated wealth increases with production, $\delta \chi_C Y$, and decreases with the consumption of the elites and the commoners

3 An Agent-Based, Complex Adaptive Systems Approach

While innovating a formal a systems approach for HANDY theory, a limitation of Motesharrei et al's [11] work lacks coupling and interdependence across human scales, from individuals to institutions and finally the societal outcomes they generate. Inspired by Motesharrei et al., our agent-based, complex adaptive systems HANDY model uniquely combines the interactive effects and feedbacks between individual human agency as well as the macro environmental constraints and opportunities that change over time for any given society. Decisions by individuals, including both elites and commoners, are affected by other individuals, social context, and system states, including accumulated wealth and resources. These decisions have variegated first and second order effects, given any particular system state, individual attributes or spatial heterogeneity. Such an approach attempts to increase both theoretical and empirical verisimilitude for some key elements of complexity processes, emergence, connectivity, interdependence and feedback [10] found across all scales of human development.

We specifically model socio-economic transaction games as producing either positive or negative values to capture both upside gains or downside losses. Subsequently, A^{ij} games' V^{ij} outcomes condition agent W^{i}_{t+1} values, modeling realized costs or benefits from any particular interaction. The updated $W^{i}_{t+1} = W^{i}_{t} + A^{ij}$ game payoff for each agent subsequently gets added to the individual's attributes for the next iteration. We then repeat individual endogenous processing, aggregated up to society as a whole and repeat the game processes for $t+n$ iterations.

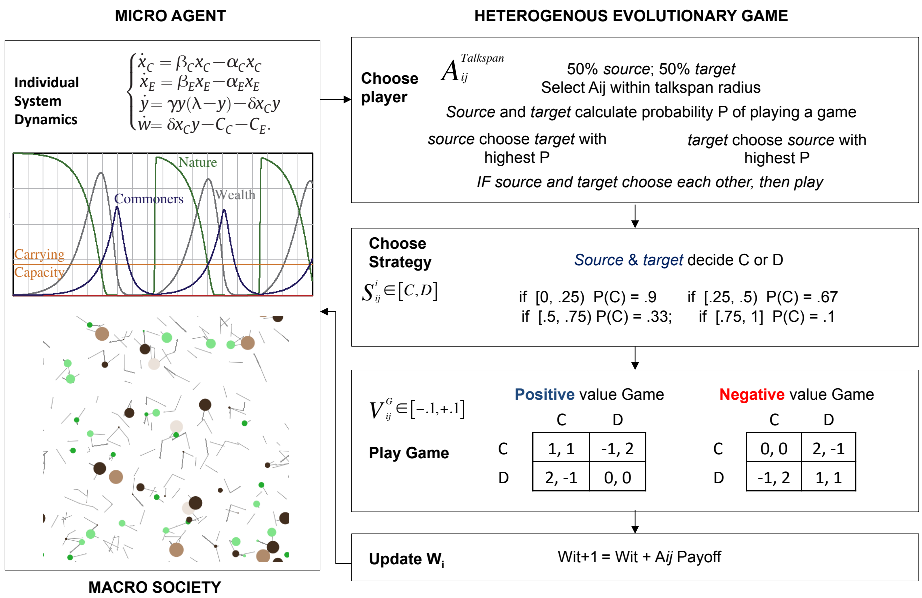

Fig.1 HANDY architecture

Aggregated wealth gets transformed into macro-society levels and impacts nature consistent with standard ecological economics as involving both inputs from, and outputs to nature, through depletion of natural sources and carrying capacity. The sum of all prior individual behavioral histories, evolutionary through iterations, does contribute to each individual and societal current states as an initial effort at a scale integrated framework. Thus agents simultaneously co-evolve as strategy pair outcomes at *t* to impact W^i at *t*+1, thus driving both positive and negative feedback process through *t*+*n* iterations. These shape A^i attributes that spur adaptation to a changing environment. Feedback into subsequent A^{ij} game selection networks and strategy choice yields a complex adaptive system representation across multiple scales. Fig.1 shows our high level architecture and agent processing.

We instantiate a non-cooperative, socio-economic Prisoner's Dilemma (PD) transaction game given agent *i*'s attribute vector (A^i) of individual agent attributes similarity to agent *j* (A^j) for any A^{ij} pairs. The motivation behind this is that individuals are more likely to interact, engage and conduct transactions with other agents of similar norms [14] and produce different co-evolutionary behavior via frequency and rate dynamics [9]. To capture complex, nonlinear and emergent behavior, we first randomly choose 50% of spatially proximal agents as sources who can choose a partner at each iteration *t*. The remaining targets are chosen by other agents based on symmetric preference rankings and asymmetric neighborhood proximity distributions. Following Abdollahian et al. [1-3] and Yang [38], we explore communications reach, social connectivity and technology diffusion that constrains the potential set of A^{ij} game pairs through talk-span.

The resulting networks provide a rich simulation dataset ripe for spectral analysis. By considering spectral gap metrics, the characteristic times between stable periods can be regressed against predictive qualities of the socio-economic transaction games networks. Following Neal [12], specifically this analysis proceeds on the basis of using mean values of the maximum eigenvalue gap max for a given *t*, the average eigenvalue gap mean, and the median eigenvalue gap median, averaged over the proceeding period of disorder. This is as opposed to using the maximum value of any of these measures observed during the disorder period, as doing so would bias longer disorder n(*t*) periods towards higher maximum observations simply by means of more draws.

We detail a generic example of the type of information and results such analysis can provide, examining whether or not the eigenspectrum of the Laplacian matrix of the system under examination is able to predict the sequence of synchronization over the examination period. Fig.2 [12] gives two such examples of thresholds which generate a monotonically decreasing number of separate components over time. The top row of Fig. 2 examines the time evolution phase of synchronization of GDP for two networks, defined by thresholds of 0.976, 0.99, respectively. The second row displays the index of eigenvalues from the Laplacian, in ascending order, against the inverse of the eigenvalues themselves, from the Laplacian matrix derived from the adjacency matrix.

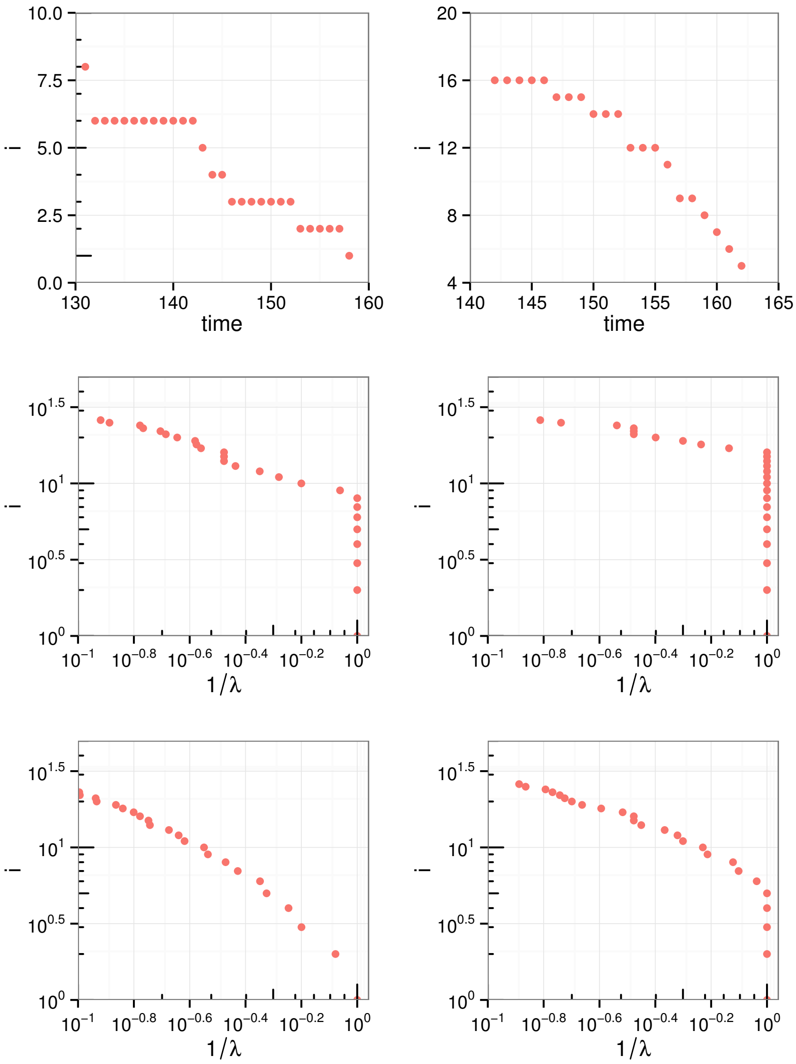

Fig.2 Floor field distribution of different algorithms

4 Results

A sample one-simulation result is visualized below in Fig. 3, with number of agents initialized at 200 and talkspan social space compression parameterized at 15 indicating medium high social connectivity. The time series plot in the center of the figure shows the level of commoner and elite populations with natural carrying capacity over time. For selected iterations *t*, we then sampled the particular agent social space to the corresponding summed time series plot. Agent size represents wealth, color represents carrying capacity ranging from darker brown indicating lower and bright green higher capacity. Edges indicate the cumulative sum of agent pairs engaged in a socio-economic transaction games from $t = 0$ to t, which could be either coercive or cooperative.

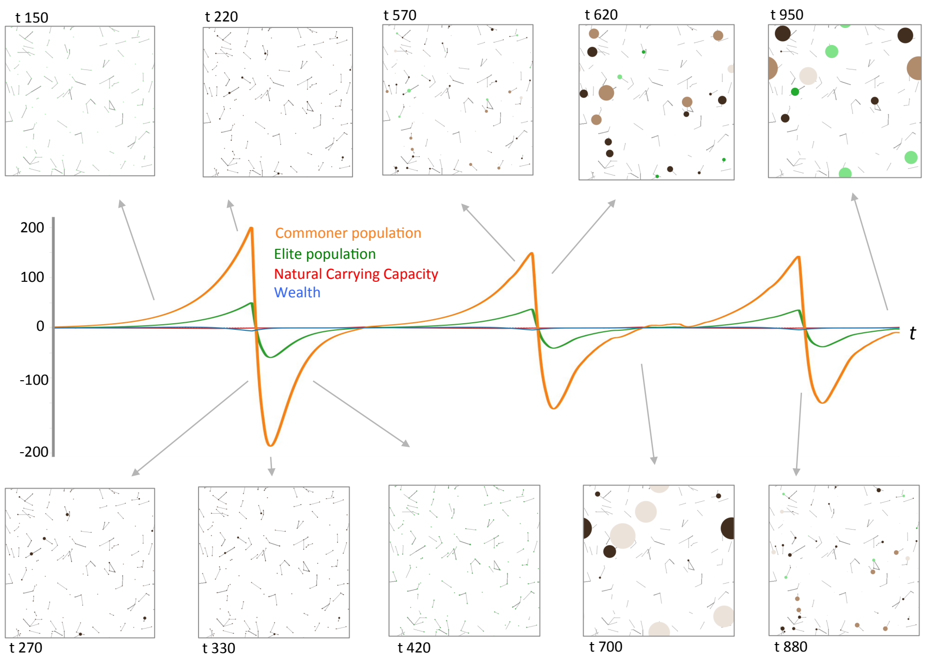

Fig.3 simulation result

Consistent with our HANDY system dynamic equations *a priori* expectation, we can see that in the time series plot cycling with strong, sharp phase transitions occurs. Both the number of commoners and elites entrainment persists although amplitude dampens over time. Levels of carrying capacity oscillate slowly, decreasing over time while wealth responds inversely, increasing marginally over time with the same frequency. In each of the agent social space plots at *t*, first we can observe that edges are consistent over time indicating the rate of socio-economic transaction games is relatively stable, regardless of population, wealth or carrying capacity concerns. When either population is positive and increasing, the carrying capacity is relatively high indicated by green agents and the converse is true with negative and decreasing series. This supports our hypotheses for high levels of carrying capacity, population and wealth increases until thresholds where there are short, sharp phase transitions, until equilibrium recovery of society where wealth continues to accumulate. Regardless of wealth levels or carrying capacity, agent interactions are likely to continue and help drive recovery phases.

5 Discussion

In the context of sustainable development, a complex adaptive systems framework can help address the coupling of nature constraint and opportunity with population dynamics and individual agency. Our work demonstrates the theoretical importance of individual agency entrainment with macro-social and environmental outcomes; how societal phase shifts and tipping points result from, and recover to, human behavior. By taking our previous research a step further with the introduction of spectral analysis on simulated social network fabrics, we contribute both to the understanding of complex, strategically driven economic societies, as well as to the understanding of the value of theoretical physics methods in a new domain. The benefit is a potentially substantial, computational cost savings in the pursuit of understanding complex games and could represent a significant advance in the practice of artificial economics.

6 References

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